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Estimating Daily Domestic Hot-Water Use in North American Homes

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ABSTRACT

Water heating in the U.S. is a major component of total energy consumption in buildings, accounting for approximately 18% of total consumption in the residential sector (EIA 2010). While there are many factors influencing hot-water energy use (location, fuel, combustion and heating efficiency, and standby losses), the actual volume of daily water to be heated is a fundamental quantity for any reasonable estimate of hot-water energy use. This study uses measured annual hot-water use in various North American climates to evaluate hot-water use in homes. The findings show that the quantity of hot-water use is correlated most closely to the mains water temperatures and the occupant demographics of the homes with 70% of the available measurement data explained when occupant demographics are well known. The study proposes a new methodology for estimating the quantities of hot-water use in homes as a function of climate location and occupancy demographics, segregating machine hot-water use, fixture hot-water use, and distribution system hot-water waste.

INTRODUCTION

Water heating in the U.S. is a major component of total energy consumption in buildings, accounting for approximately 18% of total consumption in the residential sector (EIA 2010). While there are many factors influencing hot-water energy use (location, fuel, combustion and heating efficiency, and standby losses), the actual volume of daily water to be heated is a fundamental quantity for any reasonable estimate of hot-water energy use.

Measuring hot-water volumetric consumption is more difficult than measurement of energy and thus, measurements are also more limited. Early studies on hot-water use in single-family residences included Weihl and Kempton (1985), Kempton (1986), and Perlman and Mills (1985).

Often cited, the Perlman and Mills data (1985) were taken from five residences in Toronto and another fifty homes in Ontario. Evaluation of the data showed that daily household hot-water use for a typical household of four persons was 63.1 gallons (239 liters), although with strong seasonal variation: 45.2 gallons (171 liters) per day in summer against 65.7 gallons (249 liters) in winter. Moreover, these data are potentially biased as an average as the household size in the sample was 3.8 persons.

U.S. household size—which is a large factor in hot-water demand—has dropped over time. Figure 1 shows how household size has changed since 1940, dropping precipitously from

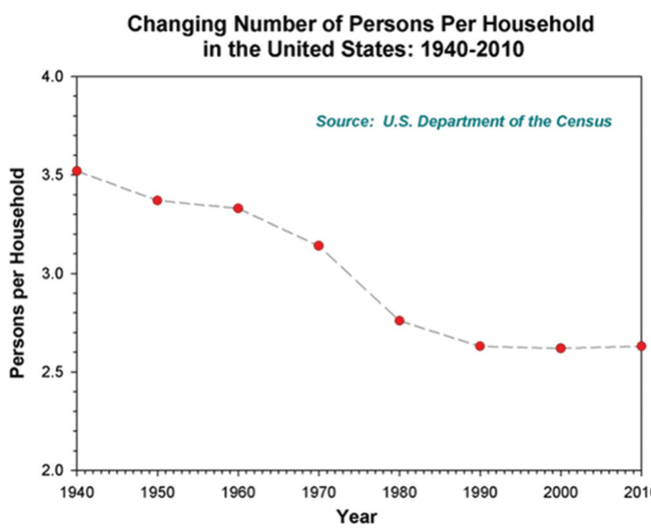

Figure 1 *Changing occupancy in U.S. households, 1940–2010.*

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1970 to 1990. Also, machine-related hot-water draws from both washing machines and dishwashers have become lower with newer, more efficient machines. In fact, it can be argued the four-person household chosen for the DOE test procedure was not typical even when ASHRAE Project RP-600 was completed. Data from 1982 to 1983 were collected when data from the U.S. Census showed that the typical occupancy of U.S. households was only about 2.8 persons.

Current occupancy is essentially unchanged since 1990. In single-family homes, occupancy is slightly greater, but in the 2009 RECS data, the average number in the household was still only 2.8 persons. Thus, a "typical" household, as termed by Perlman and Mills (1985)., is more often a three person household than one with four persons.

In a follow-on research project designed to update the data on residential hot-water use patterns, Becker and Stogsdill (1990) gathered, analyzed, and reported on nine different data sets consisting of more than 3 million data points on hot-water use in residences. This project included the data used by Perlman and Mills (1985) as well as a number of additional data sets that were gathered in both Canada and the continental U.S. This included measurements from 110 single-family residences from 11 utilities reported by Gilbert (1985), which found average household hot-water consumption to average 66.2 gallons (251 liters). Included were measurements from 142 homes in the Hood River Oregon area reported by Hirst et al. (1987) and monitoring data from 74 homes in Florida and 24 homes in North Carolina reported by Merrigan (1988). Each of these data sets contained measured hot-water use data of one year or greater in duration, from which Becker and Stogsdill reported the average hourly hot-water use in gallons for the continental U.S.

It is worthwhile examining a subset of these homes in some greater detail. Merrigan (1988), in Florida from 1982 to 1983, measured hot-water use per household to average 60.0 gallons (227 liters) per day, in 74 homes with 3.53 average occupants. Consumption was found to roughly vary with occupancy: gallons per day averaged 44, 56, 68, and 72 gallons (167, 212, 257, and 273 liters) per day in homes with 2, 3, 4, or 5 occupants, respectively. Similarly, 24 homes monitored in North Carolina (Merrigan 1988) showed average hot-water consumption of 56.9 gallons (215 liters) per day, but with the average varying seasonally: 64 gallons (242 liters) in January down to only 48 gallons (182 liters) in July.

Measurement over a year long period by Abrams and Shedd (1996) of 13 single-family homes in the Atlanta area with electric resistance water heaters showed 62.1 gallons (235 liters) per day of hot-water consumption but with strong seasonal variation. However, these homes were intentionally chosen for high-occupancy (3.77 occupants per household)—considerably greater than the typical-occupancy single family now, which is approximately 2.8 persons per household.

Considering the above data as well as the advent of more efficient hot-water fixtures and less hot water used for modern dishwashers and clothes washers, these data suggest lower average hot-water needs. Further, the dropping number of occupants per household is also important such that the 64.3 gallons (243 liters) per day reported by Department of Energy (DOE) is almost certainly high as an average by about 15%. An Electric Power Research Institute (EPRI) evaluation of a compendium of studies in the late 1990s (Hiller 1997) concluded that:

> The figure of 64.3 gallons per day which was established in the 1960s and 1970s, and is currently used in U.S. Department of Energy testing and rating procedures—isn't representative of actual use....It would appear that there is general agreement among data sets collected since the 1980s that the average hot-water consumption for single-family residences is less than 50 gallons per day.

Recent studies have included Lowenstein and Hiller (1998), Mayer et al. (1999), and Henze et al. (2002). In 14 sites, Lowenstein and Hiller (1998) saw an average hot-water consumption of 56.9 gallons (215 liters) per day with showers and baths accounting for 51% and dishwashing and clothes washing accounting for 11% and 13%, respectively. Henze et al. (2002) measured four Nebraska residences in significant detail using the flow-tracing methodology, but found only 35 gallons (132 liters) of hot-water use per day, with 59% of this coming from showers and baths, 17% from sinks, and the 10% and 12% coming from dishwashers and clothes washers, respectively.

Another study, using the flow-tracing methodology by the U.S. Environmental Protection Agency (EPA) (Aquacraft 2005), recorded hot-water use in ten homes each in Seattle and the East Bay of California in 2003. Measured hot-water use was 55.4 gallons (210 liters) in the Seattle Homes and 49.2 gallons (186 liters) per day in the East Bay homes.[1] Approximately 80% of hot-water consumption was found to come from baths, showers, and faucet use. These numbers were reduced by approximately 17%–25% by installing more water conserving fixtures, although only half of these savings came from fixtures.[2]

Another assessment done by Lutz (2005) at LBNL examined fifty studies using a flow-tracing methodology where it was concluded that average hot-water use was approximately 52.6 gallons (199 liters) per day of which approximately 20% (10.35 gallons [39 liters]) was wasted due to draws waiting for hot water to reach household service points as well as heat

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1. One caution: these studies were only of two weeks duration. As will be shown, unlike overall water use, hot water varies significantly by season as the largest end use; bath and hand washing are sensitive to temperature and thus to the mix of hot and cold to arrive at a favorable temperature—typically 105°F (40.6°C) (see Abrams and Shedd 1996). At least six months of data spanning winter and summer are necessary to obtain representative data.

2. Daily hot-water use for clothes washing in the 20 monitored homes averaged 6.7 gpd (25.4 L/d), dropping to 3.0 gpd (11.4 L/d) after more efficient horizontal-axis clothes washers were installed. Dishwasher hot-water use averaged 2.2 gpd (8.3 L/d) in the same sample. It is also interesting that the study showed that an average of 2.2 gpd (8.3 L/d) of hot-water use was due to fixture leakage.

losses from hot water remaining in piping following hot-water events. More evidence of hot-water waste and its magnitude comes from a recent study by Henderson and Wade (2014), who found an average of 22.6% hot-water waste from detailed measurements in New York homes.

For the Building America Benchmark estimation, Hendron and Engebrecht (2009) came up with an estimation procedure based on the number of bedrooms. The estimates were based on using RECS data along with some empirical data sources. The study methodology does account for seasonal variation in inlet water temperatures using a sinusoidal estimate of annual inlet water temperature based on empirical data. For showers, baths, and sinks, the water usage is based on the average of three DHW studies (Burch and Salasovich 2002; Christensen et al. 2000; CEC 2002).

MONITORED DATA

The authors compiled 105 sites of annual data where hot-water use was explicitly measured: a sample of 10 homes in Homestead, Florida; 18 houses in California; 29 homes from Minnesota; 13 in upstate New York; and 35 homes from Ottawa, Ontario. The homes had a variety of different water-heating system types spanning from natural gas and electric resistance storage tanks as well as tankless gas and combo systems. Interestingly, the investigation found no statistically systematic difference associated with water heating system type.

The overall sample had characteristics as shown in Figure 2. There were 2.75 occupants per household with 48.0 gallons (182 liters) per day of use. However, the Ottawa sample did not have important age-distribution and inlet hot-water temperature data and had fairly low occupancy in many of the homes. Thus, the sample was reduced to 69 homes from Minnesota, California, South Florida, and New York. This sample, which was used for our analysis, had 3.0 occupants per household and 51 gallons (193 liters) per day of hot-water use. Table 1 summarizes the sample.

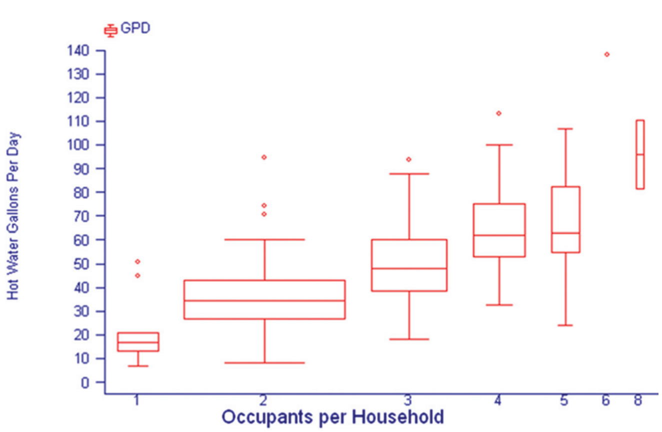

Figure 2 *Variable width box plot of gallons of hot-water use per day vs. occupants. Box width is proportional to the number of homes in the sample with that number of occupants.*

Past models of average household hot-water use have often been biased by the household size of the sample. Many older studies had households with more than three occupants, which is not typical of recent housing trends. Also, it is important to obtain information on modern fixtures and appliances. This comes largely because hot-water consumption is not only an issue related to fixtures, tanks, and plumbing, but also to hot-water consumption habits, household member behavior, and associated use.

MACHINE-RELATED HOT-WATER CONSUMPTION

Estimates on clothes washer and dishwasher hot-water use are taken from "Updated Miscellaneous Electricity Loads and Appliance Energy Usage Profiles for Use in Home Energy Ratings, the Building America Benchmark and Related Calculations," FSEC Report No. FSEC-CR-1837-10 (Parker et al. 2011), where the actual hot-water use is derived from algebraic derivation of the DOE test standards for dishwashers and clothes washers (CFR 430.32) combined with 2005 Residential Energy Consumption Survery (RECS) data on occupancy. These estimates are updated here for the RECS 2009 data based on a statistical reevaluation of occupancy to determine cycles per year for clothes washers and dishwashers. We note that while bedrooms must be used for various energy rating schemes, occupants themselves are statistically the most important drivers of the frequency of laundry and dishwashing appliance use.

Clothes Washers

$$CWcpy = 123 + 61 \times (Occ) \tag{1}$$

where

CWcpy = washer cycles per year

Occ = occupants

Given the water factor and estimated hot-water use in the DOE test procedure for washing machines, one can show that about 38% of the estimated water use (the *water factor*) is hot. However, the Cadmus report showed that about 13% of washing machine water was hot in actual metering of 115 laundry systems (Korn and Dimetrosky 2010). Other studies (detailed in the Cadmus report) showed about 18%

Table 1. Characteristics of Sample Used for Analysis

Characteristic	Value
Hot water per day	51.1 gal (193 L)
Occupants per household	3.02
Adults per household	1.90
Young adults per household	0.13
Teenagers per household	0.51
Children per household	0.55

but nothing close to 38%. Given the Cadmus study, a simple adjustment is made that the estimated hot-water use from the DOE procedure is reduced by 50% (0.5) to match what is seen in the field. Again, from FSEC Report No. FSEC-CR-1837-10, hot-water gallons per cycle are as follows:

Clothes washer hot-water use per cycle:

Standard vintage clothes washer: 8.07 gal (30.5 L) per cycle × 0.5 = 4.0 gal (15.1 L) per cycle

Standard clothes washer 2008 or later: 4.62 gal (17.5 L) per cycle × 0.5 = 2.3 gal (8.7 L) per cycle

ENERGY STAR clothes washer: 3.0 gal (11.4 L) per cycle × 0.5 = 1.5 gal (5.7 L) per cycle

As a reality check, the Cadmus study metered an average hot-water use of 3.8 gallons (14.4 liters) for standard clothes washers and 2.9 gallons (11 liters) for ENERGY STAR® washers. As another reasonability check, the Aquacraft (2005) study estimated 6.7 gallons (24.4 liters) per day in Seattle, Washington and East Bay, California in their baseline data and 3.0 gallons (11.4 liters) per day for more efficient horizontal-axis-type clothes washers.

The impact on daily hot-water gallons per day of a clothes washer is then:

$$\text{CWgpd} = \text{CWgpc} \times [(123 + 61 \times \text{Occ})/365] \quad (2)$$

Dishwashers

$$\text{DWcpy} = 91 + 30 \times (\text{Occ}) \quad (3)$$

$$\text{DWgpc} = 4.64 \times (1/\text{EF}) - 1.9295 \quad (4)$$

where

DWcpy = dishwasher cycles per year

DWgpc = dishwasher gallons per cycle

EF = dishwasher energy factor

A standard base unit has an EF of 0.46.

A minimum energy star unit (as of 2014) has an EF of 0.73 which results in the following:

- Base unit: 8.0 gallons (30.3 liters) per cycle
- ENERGY STAR unit: 4.4 gallons (16.7 liters) per cycle

Note the assumption that hand washing and a base unit dishwasher have the same impact on hot-water use (8.0 gallons [30.3 liters] per washing cycle) in that studies show no advantage to hand washing, and regression analysis in a large utility sample of 171 homes found no significant change (reduction or increase to monitored hot-water energy use) from having a dishwasher in the 81% of households in the sample with a dishwasher (Parker 2002). Adding to this conclusion is a widely cited study by Berkholz et al. (2010), which found that hand washing dishes actually uses more hot water than doing the same job with a dishwasher (13 gallons [49 liters] versus 3.4 gallons [13 liters]).

The impact on daily hot-water gallons (liters) per day of a dishwasher is then as follows:

$$\text{DWgpd} = \text{DWgpc} \times [(91 + 30 \times \text{Occ})/365] \quad (5)$$

Thus, a three-occupant home with a base unit would use 4.0 gallons (15.1 liters) per day and an ENERGY STAR unit would use 2.8 gallons (10.6 liters) per day. This compares to the Aquacraft (2005) data which showed an average 2.2 gallons (8.3 liters) per day in twenty measured households. Interestingly, three households (15% of the sample) had cold water plumbed to the dishwasher, which then did not serve to increase water heating loads.

TOTAL DAILY HOT-WATER USE

Building America Research Benchmark Definition (Hendron and Engebrecht 2009) provides a useful framework for a hot-water estimation procedure. It estimates total daily hot-water use as a function of fixture use where skin sensitivity makes the consumption temperature delivery dependent versus that for machines that are not:

$$\text{Total hot-water use} = \text{Fixture gallons per day} + \text{CWgpd} + \text{DWgpd} \quad (6)$$

For a home with three occupants and a basic clothes washer and dishwasher, the values just described are:

$$\text{CWgpd} = 4.0 \times 306/365 = 3.4 \text{ gpd (12.9 L/d])}$$

$$\text{DWgpd} = 8.0 \times 181/365 = 4.0 \text{ gpd (15.1 L/d)}$$

Fixture Hot-Water Use

In *Building America Research Benchmark Definition*, the fixture gallons (liters) per day is obtained versus household bedrooms.[3]

$$\text{Fixture gallons per day} = F_{mix} \times (30 + 10.0 \times \text{Nbr}) \quad (7)$$

where

F_{mix} = the fraction of fixture water consumption that is hot

Nbr = number of bedrooms

F_{mix} is determined by the target temperature, generally assumed to be 105°F [40.6°C] at point of end-use (T_{use}), the hot-water supply temperature (T_{set}) and the inlet mains water temperature (T_{mains}). The DOE *Building America Benchmark* procedure includes a detailed estimation procedure to show how mains water temperature varies by month:

$$T_{mains} = (T_{amb,avg} + \text{offset}) + \text{ratio} \times (\Delta\, T_{amb,max}/2) \cdot \sin(0.986 \times (\text{day\#} - 15 - \text{lag}) - 90) \quad (8)$$

where

3. The specific values for various end uses can be seen in the original reference. Showers: 14.0 + 4.67(bedrooms); baths: 3.5 + 1.17(bedrooms); other faucets: 12.5 + 4.16(bedrooms). Aggregate total= 30.0 + 10(bedrooms) × F_{mix}.

T_{mains} = mains (supply) temperature to domestic hot-water tank, °F (°C)

$T_{amb,avg}$ = annual average ambient air temperature, °F (°C)

$\Delta T_{amb,max}$ = maximum difference between monthly average ambient temperatures (e.g., $T_{amb,avg,july} - T_{amb,avg,january}$), °F (°C)

0.986 = degrees/day (360/365)

day# = Julian day of the year (1–365)

offset = 6°F (3.3°C)

ratio = $0.4 + 0.01\ (T_{amb,avg} - 44)$

lag = $35 - 1.0\ (T_{amb,avg} - 44)$

This equation is based on analysis by Burch and Christensen of NREL using measured inlet water temperature data from multiple locations (2007). Practically, however, if seasonal accuracy is not needed, the annual average is equal to the average mains water temperature, which is generally found to be the average annual air temperature plus 6°F (3.3°C).[4] The average annual temperature is available from the source TMY3 data for relevant locations in North America.

The fraction of the water use for bathing, showers and faucet is based on F_{mix}, which is determined as follows:

$$F_{mix} = 1 - [(T_{set} - T_{mix})/(T_{set} - T_{mains})] \quad (9)$$

A study of 127 homes with electric resistance water heaters in Central Florida (Parker 2002) showed that audited hot-water set temperature averaged 127°F (52.8°C) (Std. Dev: 11.5°F [6.4°C]) and field measurement studies in California by Lutz (2012) showed the median average hot-water set temperature to be 123°F (50.6°C). Here, we simplify and assume that 125°F (51.7°C) is a good average for hot-water storage temperature.

In Central Florida, where T_{amb} averages 75°F (23.9°C), so that the variables going into the model are as follows:

T_{mix}: 105°F (40.6°C)

T_{set}: 125°F (51.7°C)

T_{mains}: 81°F (27.2°C)

Under these parameters, F_{mix} is 0.545; total daily hot-water use for a three-person home using Equation 7 would calculate the following:

Fixture hot water = 32.7 gal (124 L) per day

Total hot water = fixture gal per day + CWgpd + DWgpd

Total hot water = 32.7 gal/day + 3.4 + 4.0 = 40.1 gal (152 L) per day

In Duluth, Minnesota, with an annual average T_{amb} of 39°F (3.9°C), the value for F_{mix} would be 0.75 and the fixture hot-water use would climb to 45.0 gallons (170 liters) per day, yielding total hot-water consumption of 52.4 gallons (198 liters) per day. In San Francisco, with an average annual temperature of 57°F (13.9°C), the value for F_{mix} would be 0.677 and total consumption would be 48.0 gallons (182 liters) per day.

In 1992, the Energy Policy Act of 1992 went into effect, although the market changed by 1997–1998 as existing plumbing fixture inventory was depleted (Selover 2012). This limited showerheads to 2.5 gallons per minute (0.158 liters per second) and faucets to 2.2 gallons per minute (0.139 liters per second). If the home was built before 1997 (or not remodeled and using pre-1997 plumbing fixtures), it would be reasonable to increase the fixture gallons by approximately 10%, based on the Aquacraft (2005) data, which showed older fixtures lead to increased consumption, particularly for showers and faucets. It is noteworthy that the same report showed that while special water-saving showers may save 20% or more of water, the measured reduction to hot water was much less—likely due to an altered mix for optimal shower temperature.

MAKING IMPROVEMENTS TO THE BUILDING AMERICA MODEL

Examination of the data shows a differing form of the relationship of gallons (liters) to occupants than seen in the Building America model, which is correlated based on number of bedrooms (Nbr) as shown in Equation 10 below.

$$\text{Current NREL model} = [30 + 10(\text{Nbr})] \times F_{mix} \quad (10)$$

4. It is useful to note that for analysis of water heating systems with strong seasonality in performance, such as solar or heat pump water heaters, it is probably useful to consider the seasonal variation in water heating loads since the performance of such systems are lower in months where water heating loads are highest.

Table a. Regression A: Regression of Gallons per Day by Normalized Occupancy

.regress gpd OccNorm if obs < 70				Number of obs =		69
				$F(1, 67)$ =		64.52
Source	**SS**	**df**	**MS**	Prob > F =		0.0000
Model	28156.081	1	28156.081	R-squared =		0.4906
Residual	29240.539	67	436.42595	Adj. R-squared =		0.4829
Total	57396.62	68	844.06793	Root MSE =		20.891
gpd	**Coef.**	**Std. Err.**	***t***	***P*>|*t*|**	**95% Conf. Interval**	
OccNorm	22.08464	2.749537	8.03	0.000	16.59654	27.57274
_cons	7.033017	6.038422	1.16	0.248	–5.019724	19.08576

F_{mix} is the fraction of occupancy uses that are hot based on water inlet temperatures. We created a new variable, OccNorm, which is the occupancy times the F_{mix} value computed for that location that expresses preference for fixture related hot-water use. We then regress on the measured hot-water gallons (liters) per day against the occupancy normalized for inlet water temperatures in our sample of 69 homes with reasonably complete data (see Table a).

We assume the intercept term represents the machine related hot-water draws. This works well as the computed machine related hot-water use from the data set is 7.3 gallons (27.6 liters) per day, very similar to the intercept in the above regression.

$$\text{HWgpd} = 22 \times (\text{Occ} \times F_{mix}) + \text{CWgpd} + \text{DWgpd} \quad (11)$$

F_{mix} averaged 0.68 across the sites where most of the inlet water temps were measured.

Example: three occupants and $F_{mix} = 0.68$.

Standard clothes washer and dishwasher with three occupants = 7.4 gallons (28 liters) per day.

The new model from the data is as follows:

$$\text{HWgpd} = (22 \times 3 \times F_{mix}) + 7.4 = 52.3 \text{ gpd } (198 \text{ L/d}) \quad (12)$$

The original BA hot-water model is solely meant for bedrooms and not occupants, but in that case one must adjust for the relationship of occupants and bedrooms in single-family homes. The relationship of occupants to bedrooms is established from the 2009 RECS data (as shown in Table b).

Thus, for the purposes of using the relationships shown above, the assumed occupancy per bedroom is shown in Table 2.

Since occupancy does not differ a lot with bedrooms, some of the fixed nature of the Building America model will reappear in any version of the calculations focused solely on bedrooms rather than occupancy. However, the resulting influence on potential accuracy is important—most of the predictive ability of any estimation of daily hot-water use will depend on numbers of occupants and their ages—and not on bedrooms, which is a poorer predictor. The new relationship has a stronger response relative to occupancy as the old Building America definition was focused on bedrooms instead.

Statistical Analysis of Occupant Demographic Influences

Given the indicated importance of occupant demographics from ANOVA tests to the individual variables, we use data from the first 69 homes where we have good occupant data. A stepwise regression method is used with variables removed to yield the most simple, yet powerful explanation of the variation in our data:

The stepwise regression was run with a $p < 0.1$ required to keep statistically influential independent variables in the model. The stepwise regression (see Table c) drops adult occupants as not significantly different from occupants in general. However, youth and child counts are highly significant—as seen from early review of the CA data alone. Youths (13 to 23, inclusive) are much different than older adults. They use approximately 13 gallons (49 liters) more per day. By way of balance, children use less. We also note that the coefficient of determination, R-squared, increases dramatically from 0.49 to 0.71 within the same data set. Once we consider occupant demographics, we do much better at predicting hot-water loads. What would the above model indicate for the following three-occupant households ($F_{mix} = 0.68$)?

- Three adult occupants, no kids: 46.6 gpd (176 L/d)
- Two adults; one child: 41.2 gpd (156 L/d)
- One single parent: two children: 35.8 gpd (136 L/d)
- Two adults: one teen: 59.6 gpd (226 L/d)
- One single parent; two youths: 72.6 gpd (275 L/d)
- Three college kids in a rental: 85.6 gpd (324 L/d)

Table b. Regression B: Occupancy versus Bedrooms in Single Family Homes

. reg occupants bedrooms if SF = 1				Number of obs =	8693	
				$F(1, 8691)$ =	1001.94	
Source	**SS**	**df**	**MS**	Prob > F =	0.0000	
Model	2097.6268	1	2097.6268	R-squared =	0.1034	
Residual	18195.216	8691	2.0935698	Adj R-squared =	0.1033	
Total	20292.842	8692	2.3346574	Root MSE =	1.4469	
Occupants	**Coef.**	**Std. Err.**	t	**P>|t|**	**95% Conf. Interval**	
bedrooms	0.5396171	0.0170477	31.65	0.000	0.5061996	0.5730346
_cons	1.094259	0.0567196	19.29	0.000	0.9830749	1.205443

Even ignoring the three college students scenario, we see a 2:1 difference indicated for hot-water consumption from the age-related consumption characteristics to the occupancy of the household. Household demographics appear to matter quite a bit for estimating site-specific hot-water consumption. Of course, across buildings and over their useful life, these factors cancel out. However, they are potentially useful relative to understanding variance, for sizing related issues and to predict immediate retrofit savings from water heating technology changes in specific households.

This allows an accuracy approaching 70% at predicting variation in hot-water consumption, but without understanding that a portion of the occupancy-related hot-water use is actually arising from waste rather than intrinsic use for bathing, washing, etc.

Hot-Water Waste

Explicit within Equation 11 is the fact that the occupant coefficient is derived from measured annual hot-water use in homes. Thus, the result of applying the equation *a priori* includes any hot-water waste associated with the hot-water distribution system. Structural waste in hot-water distribution systems arises from the fact that following a hot-water event, the hot water in the piping loses heat to its surroundings. The quantity of hot-water waste that a distribution system experiences is dependent on three principle factors:

- The length and diameter of the hot-water piping between the hot-water heater and the point of hot-water use (i.e., the volume of hot water that can be left in the piping)
- The amount of insulation on the hot-water piping
- The elapsed time between multiple hot-water events that use the same piping

The first two of these factors are self-evident and have been measured in laboratory tests by Hiller (2005 and 2006) but the third factor can be more difficult to grasp. The time interval between multiple hot-water events that use the same piping is important because it determines the quantity of heat that will be lost from the piping between hot-water events. If two hot-water events follow one another within a very short time period (e.g., two showers, one right after another), the hot-water waste quantity will be very similar to a single event. However, if sufficient time elapses between two events, then all of the residual hot water left in the piping following both events will be lost to the surroundings. Klein (2012) has estimated that for all practical purposes, if two events are separated by 45 minutes or more, there will be no useful residual hot water left in the hot-water distribution piping.

Hot-water waste is difficult to measure and has been measured and reported for only a small quantity of homes. Henderson and Wade (2014) measured hot-water waste in five New York homes and found that total hot-water waste averaged 22.6% (with a median of 17.5%). Sherman (2014) used measured hot-water data from 18 California homes to determine hot-water waste in showers at 15% of shower hot-water use, virtually matching the shower hot-water waste

Table 2. Occupants per Bedrooms from 2009 RECS Data

Bedrooms	Average Occupants
2	2.17
3	2.71
4	3.25
5	3.79

Source: 2009 RECS

Table c. Regression C: Daily DHW Gallon versus Occupancy and Demographic Variables

. sw reg gpd OccNorm adult child youth if obs < 70, pr(0.1) *p* = 0.9556 >= 0.1000

Source	SS	df	MS		
				Number of obs =	69
				$F(3, 65)$ =	52.83
				Prob > F =	0.0000
Model	40702.277	3	13567.426	R-squared =	0.7091
Residual	16694.342	65	256.83604	Adj R-squared =	0.6957
Total	57396.620	68	844.06793	Root MSE =	16.026

gpd	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
OccNorm	19.49922	3.719751	5.24	0.000	12.07036	26.92808
youth	13.04681	2.966789	4.40	0.000	7.121718	18.97189
Child	–5.358305	2.777666	–1.93	0.058	–10.90569	0.189076
_cons	6.788539	5.58808	1.21	0.229	–4.371628	17.94871

reported by Henderson and Wade (2014), who found shower hot-water waste to be 14.9%. Using data from the REUWS report (Mayer et al. 1999), Lutz (2004) estimated hot-water waste at 20%. Using plumbing layouts in typical homes along with hot-water draw profile information, Klein (2012) estimated that hot-water waste in typical homes is on the order of 10 gallons (37.8 liters) per day. At the annual average hot-water use of 50 gallons (189 liters) per day, Klein's value also equates to 20% of average total daily hot-water use. Van Decker (2014) estimates that average hot-water waste likely varies linearly from a high of 24% for single occupant homes to a low of 16% for homes with six occupants due to a decrease in the time interval between hot-water events as a function of the number of occupants. This decrease in the interval between hot-water events results in two impacts that reduce relative hot-water waste:

- Faster hot-water piping warm-up between hot-water events due to the residual hot water remaining in the hot-water piping
- Less hot-water heat loss between events

Using Equation 11 and the linear waste hot-water fractions provided by Van Decker (2014), Table 3 determines waste hot water and fixture hot water separately.

However, the waste hot-water and fixture hot-water values in Table 3 are for a specific climate and include F_{mix} within their calculation. In order to generalize waste and fixture hot-water values across all climates, it is necessary to normalize them by F_{mix}. Table 4 presents the climate-normalized values for waste and fixture hot-water use.

The climate-normalized waste and fixture use values can then be used to segregate waste hot-water and fixture hot-water use as shown in Equation 13.

$$\text{HWgpd} = \text{CW} + \text{DW} + (\text{nFgpd} + \text{nWgpd}) \times F_{mix} \qquad (13)$$

The appropriate expressions for nFgdp and nWgdp can be found by regression of the data in Table 4. Figures 3 and 4 present these regressions in graphic form. Note in Figure 3 that the actual curve is parabolic with a declining estimated amount of wasted hot water with increasing occupancy.

Table 3. Predicted Daily Hot-Water Use by Number of Occupants in Accordance with Equation 11

Occupants	DW + CW*	F_{mix}†	HWgpd**	% Waste‡	Wgpd***	Fgpd****
1	4.7	0.676	19.5	24.0%	4.69	10.19
2	6.0	0.676	35.8	22.4%	8.01	21.75
3	7.3	0.676	52.0	20.8%	10.81	33.83
4	8.6	0.676	68.2	19.2%	13.09	46.43
5	10.0	0.676	84.4	17.6%	14.85	59.55
6	11.3	0.676	100.6	16.0%	16.09	73.19

* = Sum of dishwasher and clothes washer hot-water gallons per day
† = hot-water mix fraction to achieve useful temperature (T_{mains} = 63.2°F [17.3°C])
** = total hot-water gallons per day
‡ = percentage of HWgpd that is wasted
*** = waste hot-water gallons per day
**** = fixture hot-water gallons per day

Table 4. Climate Normalized Values for Hot-Water Waste and Fixture Use

Occupants	nWgpd	nFgpd
1	6.9	15.1
2	11.8	32.2
3	16.0	50.0
4	19.4	68.6
5	22.0	88.0
6	23.8	108.2

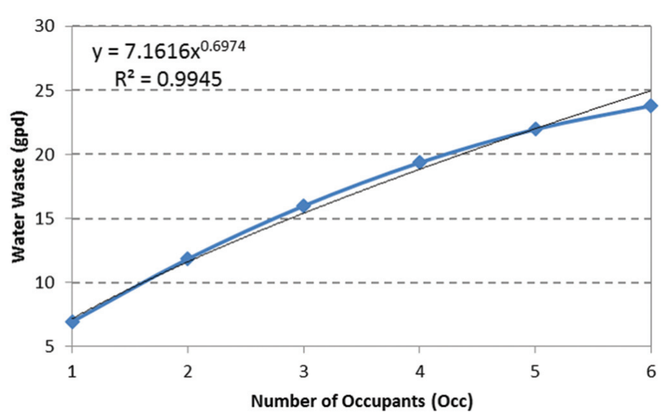

Figure 3 Fit of wasted hot water to occupants.

Now we have values in terms of the number of occupants in the home, that can be used in Equation 11 to determine hot-water use generally and also can segregate the waste hot water from the fixture hot-water use. This enables hot-water distribution system effectiveness to be addressed through the waste hot-water term. Another first order estimate for influence of fixture efficiency can be added as well. Equation 14 then becomes:

$$HWgpd = CW + DW + [(18.6 \times Occ - 4.84) + (7.16 \times Occ^{0.7})] \times F_{mix} \times Vintage_{FR} \quad (14)$$

where

$Vintage_{FR} = 1.10 - 0.10 \times$ fraction of fixtures post 1995 that meet EPACT 1992

Formulation of an Improved Hot-Water Prediction Model

The new model as shown above can be used to comprehensively estimate daily household hot-water use. We used Equation 14 on the entire set of 69 homes to predict hot-water consumption.

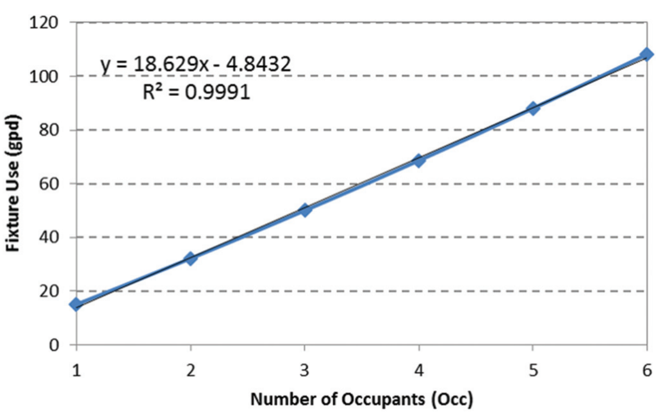

Figure 4 *Fit of fixture hot water to occupants.*

A regression of predicted versus measured gallons (liters) per day (see Table d) revealed that the proposed calculation explains about 48% of the measured variation in daily hot-water use.

We then subjected the measured gallons (liters) of hot water to the result from a regression of the estimate of Equation 14 and then considered how the household demographic variables might influence the results for specific households.

First, we calculated a residual between the estimated consumption:

$$Residual = DHW\_GPD - NewPred$$

We then regressed the residual versus the demographic variables, youth and child, each normalized by F_{mix} (see Table e):

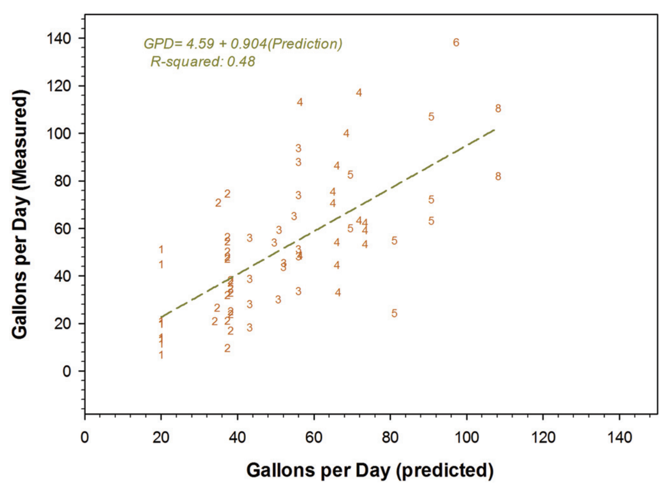

Figure 5 *Comparison between measured (DHW_GPD) and predicted hot-water use (NewPred). Plot symbols are the number of reported household occupants.*

Table d. Regression D: Correspondence of New Model of Hot Water Use versus Measurements

. reg gpd NewPred if obs < 70					
				Number of obs =	69
				$F(1, 67)$ =	61.38
Source	**SS**	**df**	**MS**	Prob > F =	0.0000
Model	27442.287	1	27442.287	R-squared =	0.4781
Residual	29954.333	67	447.07959	Adj R-squared =	0.4703
Total	57396.620	68	844.06793	Root MSE =	21.144

gpd	**Coef.**	**Std. Err.**	***t***	***P*>|*t*|**	**[95% Conf. Interval]**	
NewPred	0.9038205	0.1153624	7.83	0.000	0.6735561	1.134085
_cons	4.59519	6.461812	0.71	0.479	–8.302642	17.49302

The revised prediction incorporating demographic characteristics of the household is then:

$$\text{Dem\_Pred} = \text{NewPred} - 2.7 + 16.6\,(\text{Youth} \times F_{mix}) - 13.6\,(\text{Child} \times F_{mix}) \quad (15)$$

where

Youth = number of occupants aged 13–23 years

Child = number of occupants that are 0–6 years in age

The result produces a large increase in correspondence of measured to predicted values:

The revised prediction incorporating information about youths and children in the household can explain 70% of the variation in measured consumption (see Table f). The prediction improvement is illustrated in Figure 6.

Note that if bedrooms, rather than occupants, are to be used with the relationship, the values shown in shown in Table 2 should be substituted into the occupants variable based on the preceding analysis of occupancy versus bedrooms. The ability of this relationship to predict hot-water consumption will be worse than either of the above two forms where actual number of occupants was found to be important to accurate prediction. Applications using bedrooms instead of occupants are discussed below.

New Homes

For many applications, the number and age characteristics of home occupants are not known. For example, home energy ratings and code calculations are performed for homes that have not yet been occupied. While the characteristics of home occupancy is shown to be the best predictor of hot-water use in homes, the data also show that the best surrogate for occupancy is the number of bedrooms in the home.

RESNET has used the procedure described in this paper to characterize hot-water use for single-family homes in terms of the number of bedrooms in the home (RESNET 2014). The 2009 RECS data is used to develop the statistical relationship between the number of bedrooms and the number of occupants likely to occupy homes. Assuming that occupant behavior with respect to

Table e. Regression E: Regression of New Model Residuals versus Demographic Variables

. reg res youth_mix child_mix if obs < 70						
				Number of obs =		69
				$F(2, 66)$ =		24.79
Source	**SS**	**df**	**MS**	Prob > F =		0.0000
Model	12982.181	2	6491.0907	R-squared =		0.4289
Residual	17282.909	66	261.86225	Adj R-squared =		0.4116
Total	30265.09	68	445.07485	Root MSE =		16.182
res	**Coef.**	**Std. Err.**	***t***	***P*>|*t*|**	**[95% Conf. Interval]**	
youth_mix	16.64199	3.336123	4.99	0.000	9.9812	23.30277
child_mix	–13.58008	3.066118	–4.43	0.000	–19.70178	–7.458378
_cons	–2.653348	2.673757	–0.99	0.325	–7.991676	2.68498

Table f. Regression F: Success of Final Demographic Model in Reproducing Measured Results

. reg gpd DemPred if obs < 70						
				Number of obs =		69
				$F(1, 67)$ =		156.92
Source	**SS**	**df**	**MS**	Prob > F =		0.0000
Model	40222.835	1	40222.835	R-squared =		0.7008
Residual	17173.785	67	256.32515	Adj R-squared =		0.6963
Total	57396.620	68	844.06793	Root MSE =		16.01
gpd	**Coef.**	**Std. Err.**	***t***	***P*>|*t*|**	**[95% Conf. Interval]**	
DemPred	0.9504925	0.0758766	12.53	0.000	0.7990422	1.101943
_cons	2.531194	4.331799	0.58	0.561	–6.115113	11.1775

hot-water use does not vary greatly depending on home type, this same procedure can be used to develop fixture and waste water use in other home types as well. Using the statistical bedroom-to-occupancy relationships developed from 2009 RECS data, Table 5 provides the climate-normalized fixture and waste hot-water equations that can be used in Equation 13 to estimate fixture and waste hot-water use in residences of various types where the occupancy characteristics are not explicitly known.

SUMMARY

A new hot-water prediction model has been described. The model takes into account, consumption due to occupancy. It also considers the following significant factors:

- Number of household occupants and location dependent inlet water temperature can explain about 50% of the variation in observed variation in hot-water consumption.
- Age-related distribution of the occupants appears to explain about further 20% of the occupancy related variation. Teenagers use more hot water and young children use less.

Table 5. Climate-Normalized Fixture (nFgpd) and Waste (nWgpd) Gallons per Day as a Function of the Number of Bedrooms (BR) in a Home

Home Type	Occupants/ Bedroom	nFgpd	nWgpd
Single-family	1.09 + 0.54 × BR	14.6 + 10.0 × BR	$9.8 \times BR^{0.43}$
Multi-family	1.49 + 0.45 × BR	21.9 + 8.3 × BR	$11.2 \times BR^{0.34}$
Low income multifamily	1.69 + 0.57 × BR	25.2 + 10.7 × BR	$12.9 \times BR^{0.32}$

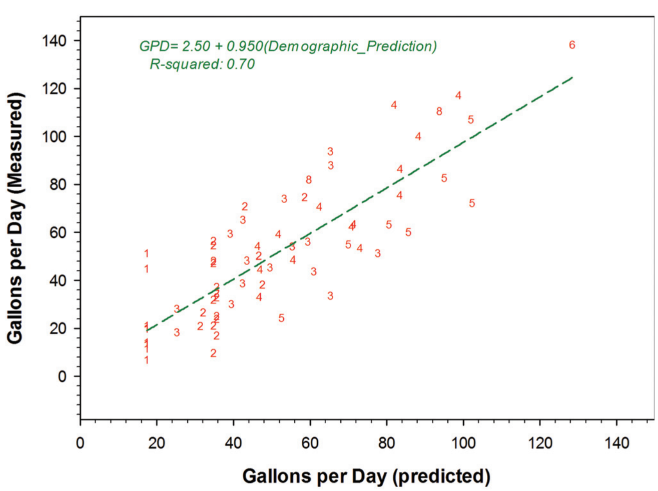

Figure 6 *Comparison between measured (DHW_GPD) and predicted hot-water use incorporating information on ages of household occupants. Plot symbols are the number of household occupants.*

- How bathing and faucet hot-water consumption varies with climate and seasonality to reach the optimal temperature for skin sensitive uses (~105°F [40.6°C]).
- We develop a method to approximate the quantity of hot water wasted to enable the water to reach the point of end use at a satisfactory temperature.
- Machine-related consumption from clothes washers and dishwashers is included.

Our results show that occupancy—and particularly, the age of the occupants—are major factors influencing site specific consumption. All other factors held equal, young adults and teenagers use considerably more hot water than other occupants. The model is able to explain approximately 70% of the variation in measured hot-water consumption from three empirical data sets where average daily hot-water use was directly measured.

The explanatory power is much reduced, however, when only data on occupancy is available (or even less when only data on number of bedrooms is considered). In such cases, only about 25% of the observed variation in consumption can be explained. Of course from a policy perspective a building will undergo a changing age distribution of its occupants as well as the number of occupants itself. Accordingly, building-related models focused on the number of bedrooms will be largely unable to account for observed variation in hot-water use—an artifact of the loose relationship between occupants and bedrooms. Errors in predicting hot-water use in specific buildings will be necessarily approximate.

There remains stochastic variation in occupancy-related variation that cannot be readily accounted for in a prediction model. As human behavior is involved, such models will always necessarily be coarse. However, cited studies do show that other physical factors (particularly fixture leakage) likely account for some of the remaining variation.

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